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TECHNIQUES FOR OPTICAL COMMUNICATION SYSTEMS
Final Report (University of Southern Calif.)
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UNIVERSITY OF SOUTHERN CALIFORNIA

A STUDY OF SYNCHRONIZATION TECHNIQUES

FOR OPTICAL COMMUNICATION SYSTEMS

R. M. Gagliardi

January 1975
Final Technical Report

PRICES SUBJECT TO CHANGE

Prepared for
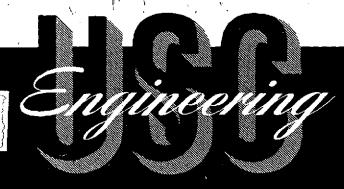
National Aeronautics and Space Administration
Office of University Affairs
Washington, D. C.   20546

ELECTRONIC SCIENCES LABORATORY

Engineering USC

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1. INTRODUCTION

This document is a final report of work done in the Department of Electrical Engineering at the University of Southern California for the National Aeronautics and Space Administration, in the area of optical communications. The work effort was carried out under the guidance of Professor Robert M. Gagliardi of the Electrical Engineering Department, and covered an extended period commencing in 1969 and ending January 31, 1975. The work was initiated as a joint research effort between the University of Southern California and NASA's Electronic Research Center in Cambridge, Massachusetts. The work was later monitored by the Electro-optics Division at the Goddard Spaceflight Center at Greenbelt, Maryland. The contract was funded by NASA's Office of University Affairs under Grant NGL 05-018-104.

The objective of the program was to study synchronization techniques and related topics in the design of high data rate, deep space, optical communication systems. The research was solely analytical in nature and was divided into two basic categories. The first involves tasks with direct application to the time synchronization problem, while the second involves related areas also being studied under the grant. The study was to indicate design procedures, assess system performance and predict future areas of needed study in synthesizing and improving digital optical systems.

This final report reviews the program objectives, the significant results, and the published research work generated during the program tenure.

2. PROGRAM OBJECTIVE

This study program was initiated in December 1968 at a time when NASA was vitally interested in developing a high data rate, deep space, optical communication system. The primary mode of operation was to be direct detection digital transmission, with interest in possible block encoding to achieve improved data rates. Use of narrow pulsed optical sources was expected to be the principle signalling format. At that time, some questions existed concerning the ability to time synchronize low duty cycle optical systems for bit and word detection. For these reasons the study program was initiated.

The specific work tasks of the program were:

1) To determine the effect of timing errors in narrow pulsed digital optical systems. This task would allow for a determination of the required timing needed in system design in order to maintain necessary temporal coherence. At the time of program commencement accurate statistical models for optical detection were only partially known. Thus, a subtask here was the development of usable system models for analysis of bit and word error probabilities for both perfect and imperfectly timed systems.

2) To determine the accuracy to which well known microwave timing systems can be operated in a low powered optical system.

3) To derive improved tracking systems for the optical channel. Also, to determine the degree of improvement that can be expected by

these newer systems, and possible upper bounds to tracking performance. This would allow comparison to present state of the art systems currently in existence, for a cost effective study of redesigning synchronization systems.

Other areas of interest closely related to the above primary tasks were also to be considered:

4) An establishment of a usable photodetector mathematical model for application to the analysis and design of performance in a communication receiver.

5) A study of the application of multi-level block encoding to the optical transmissions of digital data, and possible improvements in transmitted information rates.

3. <u>SUMMARY OF PROGRAM ACCOMPLISHMENTS AND RESULTS</u>

Since the study effort was solely analytical in nature, the results

of the program were technical reports, summarizing the achieved

milestones. The program produced a total of 11 technical reports,

12 published papers, and 2 Ph.D. dissertations. The key accomplish-

ments of the program are summarized below. References refer to

the listed reports in Section 4, where the stated results are documented.

1) Developed an accurate mathematical model of the photodetecting

receiver and its statistical properties for use in digital receiver design.

Specifically, a detailed study was made of the detector shot noise process

and its interrelation with the counting processes that govern it. Investi-

gation of the conditional Poisson counting process (referred to more

recently as a doubly stochastic Poisson process) was made in depth,

exploring the relation of Poisson, Laguerre, and Bose-Einstein counting.

The relation of optical shot noise to Gaussian processes was studied.

References - Section 4.1 [4, 6, 7]; Section 4.2 [3, 4, 6].

2) Studied the pulse position modulated (PPM) mode of optical

digital transmission, showing its optimality and practical system

implementation. The results were extended to block encoded systems

and resulting error probabilities were derived. A computer program

was developed for computation of PPM system performance under all

possible operating conditions. Section 4.1 [1, 2, 3]; Section 4.2 [1, 2, 6, 9].

3) Determined the effects of timing errors in both PPM and on-off

keyed digital systems. Section 4.1 [8]; Section 4.2 [5, 7].

4) Determined the ability to time and phase lock in phase and pulse tracking subsystems following photodetection in direct detection optical systems. Relations between tracking errors and operating signal to noise ratio were developed. Section 4.1 [5,9]; Section 4.2 [11]; Section 4.3 [1].

5) Determined the optimal tracking system for optical systems. The approach here was to invoke the use of estimation theory and treat the tracking problem as one of estimating arrival time of a synchronizing signal. The optimal tracker was then determined as an optimal estimator of arrival time. This also allowed for a study of signal wave-shape for best obtaining the timing information. Section 4.1 [10]; Section 4.2 [10].

6) Investigated digital signalling procedures other than PPM that aid in overcoming the time accuracy problem. Although PPM systems are optimal for perfectly timed systems, it was shown that use of noncoherent, multi-level frequency shift keyed systems using harmonic square waves are more efficient at high data rates. This study effort represents a new area of research not included in the task statement. Studies in this area are not completed. Section 4.1 [11]; Section 4.2 [12]; Section 4.3 [2].

7) Extended the problem of time tracking to spatial pointing, acquisition, and spatial tracking. Developed the relationship among power levels, pointing accuracy, performance, and acquisition times in locating spatially positioned transmitters. Computer programs have

been developed for this purpose. Studies in this area are still under

investigation and research has not been completed.

There were not patents or inventions produced from this research.

4. PROGRAM DOCUMENT LIST

The following lists all research and technical reports, published papers, and documents generated from, and accredited to, this study grant.

4.1 Technical Reports

A 69-1055 [1] NASA Technical Note TN D-4623, "M-ary Poisson Detection and Optical Communications," S. Karp and R. Gagliardi, June 1968.

A70-21778 [2] NASA Technical Note TN D-4814, "Design of PPM Optical Communication Systems," S. Karp and R. Gagliardi, October 1968.

[3] NASA Technical Note TN C-40, "Error Probabilities for Detection of M-ary Poisson Processes in Poisson Noise," S. Karp, G. Hurwitz and R. Gagliardi, May 1968.

A70-27446 [4] USCEE Report 334, "On the Representation of Continuous Stochastic Intensities by Poisson Shot Noite," R. Gagliardi and S. Karp, March 1969.

N70-42094 [5] USCEE Report 396, "Optical Synchronization - Phase Locking With Shot Noise Processes," R. Gagliardi and M. Haney, August 1970.

A71-17085 [6] USCEE Report 397, "Communication Theory for the Free Space Optical Channel," R. Gagliardi, S. Karp and E. O'Niell, August 1970.

X71-79821 [7] USCEE Report 401, "Counting Statistics for Extended Optical Photodetectors," R. Gagliardi and V. Farrukh, January 1971.

A72-25885 [8] USCEE Report 406, "The Effect of Timing Errors in Optical Digital Systems," R. Gagliardi, August 1971.

just in as system 3/14/75 [9] USCEE Report 426, "Synchronization Using Pulse Edge Detection in Optical PPM Communication Systems," R. Gagliardi, September 1972.

not in system as of 3/14/75 [10] USCEE Report 448, "MAP Synchronization in Optical Communication Systems," R. Gagliardi, N. Mohanty, April 1973.

To be published in IEEE Trans. Theory, May 1975 [11] USCEE Report 471, "Noncoherent Detection of Periodic Optical Signals," R. Gagliardi, April 1974.

4.2 Published Papers

[1] R. Gagliardi and S. Karp, "M-ary Poisson Detection and Optical Communications," IEEE Trans. on Communication Technology, Vol. CT-17, No. 2, April 1969, pp. 208. A 69-10556

[2] S. Karp and R. Gagliardi, "The Design of PPM Optical Communication Systems," IEEE Trans. on Communication Technology, Vol. CT-17, December 1969, pp. 670. A70-21778

[3] R. Gagliardi and S. Karp, "On the Representation of a Continuous Intensity by Poisson Shot Noise," IEEE Trans. on Info. Theory, Vol. IT-16, No. 2, March 1970. A702-7418

[4] S. Karp, R. Gagliardi and E. O'Neill, "Communication Theory for the Free Space Optical Channel," Proc. of the IEEE, Vol. 58, No. 10, October 1970, pp. 1611. A71-17085

[5] R. Gagliardi, "On the Timing Problem in Optical Digita Systems," Proceedings of the International Telemetry Conference, September 1971, Washington, D. C. A72-12141

[6] R. Gagliardi, "Photon Counting and Laguerre Detection," IEEE Trans. on Info. Theory, Vol. IT-18, January 1972, pp. 208. A72-18394

[7] R. Gagliardi, "The Effect of Timing Errors in Optical Digital Systems," IEEE Trans. on Communication Technology, Vol. CT-20, No. 2, April 1972. A72-25885

[8] N. C. Mohanty, "On the Identifiability of Finite Mixtures of Laguerre Distributions," IEEE Trans. on Information Theory, Vol. IT-18, No. 4, July 1972. A73-36984

[9] N. C. Mohanty, "M-ary Laguerre Detection," IEEE Trans. on Aerospace and Electronic Systems, Vol. AES, May 1973. A73-31734

[10] N. C. Mohanty, "Estimation of Delay of M PMM Signals in Laguerre Communications," IEEE Trans. on Communication, Vol. COM-22, No. 5, May 1974.

[11] R. Gagliardi, "Synchronization Using Pulse Edge Tracking in Optical PPM Communication Systems," IEEE Trans. on Comm., Vol. COM-22, No. 10, October 1974.

[12] R. Gagliardi, "Noncoherent Detection of Periodic Optical Pulses," IEEE Trans. on Information Theory, Vol. IT-5, May 1975 (to be published).

4.3 Ph.D. Dissertations

[1] "Phase Locked Loop Tracking of Shot Noise Processes," by George Michael Haney, presented to the Graduate School of the University of Southern California, January 1971.

[2] "Non-coherent Detection of Subcarrier Frequencies in Direct Detection Optical Communication Systems," by Richard A. Maag, presented to the Graduate School of the University of Southern California, February, 1975 (to be published).

5. APPENDIX

Reprints of most of the reports in Section 4 are included. When a report appeared as both a technical document and a published paper, only the paper was included. The reports included are listed in the following order: [numbers refer to their listing in Section 4.]

4.2   [1]
         [2]
         [3]
         [4]
         [6]
         [7]
         [8]
         [9]
         [10]
4.1   [5]
         [10]
         [11]